Stem-Flow Gauges for Measurement of Crop Water Use.

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Abstract

Over the last five years new advances in the techniques for sap-flow measurements have made the measurement of water use in crops, trees and vines a simple process to monitor. The method has been studied, and research has proven the utility of the constant heat stem-heat balance (SHB) method of determining transpiration (T) and how it relates to sap flow (F). Many species of crops have been measured in the field under realistic conditions, and studies are proving the utility of the method in a variety of applications of Dynagages. Citrus and fruit growing applications have recently been explored, and SHB is shown to be useful in determining water stress and in relating water consumed to the amount of hourly or daily evapotranspiration (ETP) demand. After several years of development, the need became apparent for evaluation of more numerous samples, and the author developed a system whereby up to 32 plants can be monitored simultaneously and real time results can be displayed. The Flow32 tm System makes crop and citrus applications for the farmer, horticulturist, irrigation specialist, and researchers an indispensable addition to the tools needed to keep crop production at a peak, while minimizing water use, preventing drought stress, and monitoring growth patterns relative to environmental changes. Although many more species need to be tested using stem-flow technology, many of the principal economic crops of the world have been shown to be effectively monitored using Dynagage. Many new applications are now enabled by having complete monitoring systems available to commercial as well as research stations.

Introduction to Sap-Flow Measurement

By measuring sap flow directly with a simple and accurate means, the ageless question of how much water does a plant need to be healthy and produce up to its full potential can be answered directly. The use of a energy balance method uses the principles of thermodynamics, heat transfer, and conservation of energy to determine the amount of heat and mass flow of water moving up the stem. In Baker-van Bavel(1987), the most recent method of sap flow sensing was developed indicating that it was possible to produce a fully portable sensor which required no calibration, and was non invasive nor harmful to the plant stem. Sap flow was measured in the stem of small (<16 mm diameter) herbaceous plants. On larger, woody species from 35mm to 45 mm diameter, the stem heat balance was successfully tested on Ficus retusa and Ficus benjamina ornamental trees, by (Steinberg (1988) and Steinberg- van Bavel(1989).

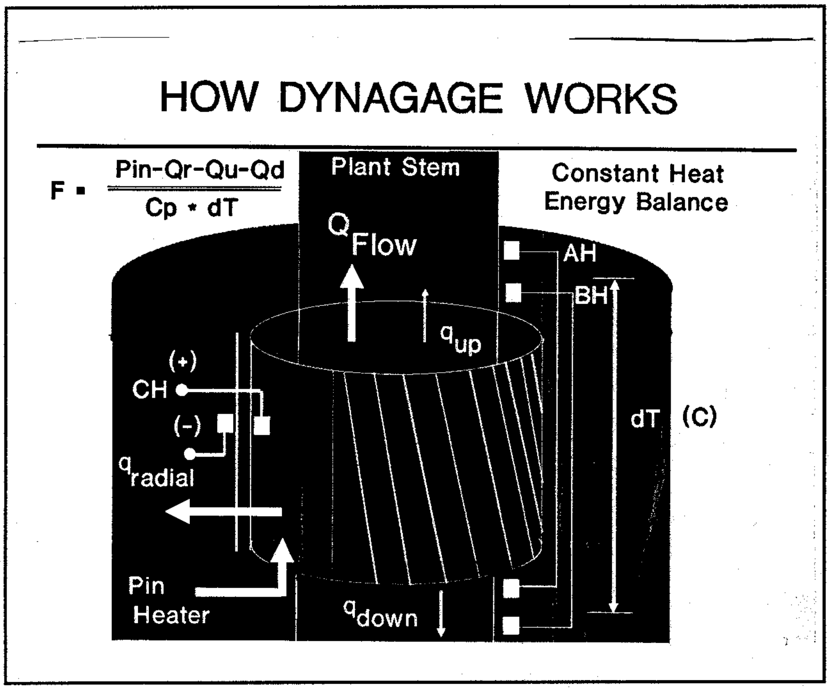
Sap flow measurement has been the subject of many research projects over the last twenty years using a variety of methods. Indirect means exist whereby lysimeters measure water loss by weighing potted plants, or calculate transpiration by the leaf stomatal conductance with a leaf porometer. However, both of these methods are limited to a few plants in an unnatural confinement of soil and roots, or have been shown to be constricted to a few data points of a periodic leaf measurement. Heat-pulse velocity (HPV) sap flow measurement has been used with some success, and relies on a calibration of sap velocity to a volumetric flow to be useful. HPV requires heating and temperature probes to be inserted into the plant stem that can affect the reading obtained. Another probe insertion method is based on an energy balance, called the trunk heat balance (THB), which applies to large trees, up to 100 cm diameter. THB requires placing a battery of five steel electrodes and eight thermocouples into the trunk xylem and using AC power to heat the sap by the current through the electrodes. This method developed by J. Cermak, and E. D. Schulze, is detailed in journals and can be useful if the experience is gained on where and how to insert the probes, as well as having a knowledge of the xylem structure.

Constant Heat - Energy Balance Method

A stem heat balance method that uses a constant power input to the heater is manufactured by Dynamax Inc, Houston Texas. Although the power is modified from time to time to maintain temperatures within practical limits, at any given time the heater within the gauge inputs energy to the stem at a constant rate. The theory and practice of the gauge is explained in the next few paragraphs. The energy balance is the following principle based on the conservation of energy:

$$Qin = Qf + Qv + Qr + Qs$$

Where Qin is the constant heat applied in Watts, Qf is the heat flux energy carried by the sap flow, Qv is the heat conducted up (qu) and down q(d) the stem axially, Qr is the heat conducted through the insulation radially to the ambient, and Qs is the heat stored in the stem test section. For most applications Qs is as-



sumed to be small and can be ignored for all but very low sap flow applications. By measuring Pin, Qu, Qd, and Qr, the remainder, Qf can be calculated. Qf is the heat convection carried by the sap. After dividing by the heat capacity of water and the temperature increase, the heat flux is converted directly to mass flow rate.

The energy balance is expressed as:

$$Qh = Qr + Qv + Qf \quad (W) \qquad (1)$$

$$Qh = Pin = V^2 / R$$ from Ohms Law.

Fourier's Law describes the vertical conduction components:

$$Qv = Qu + Qd$$

Where

$$Qu = Kst\ A\ dTu / dX$$
$$Qd = Kst\ A\ dTd / dX$$

where Kst is the thermal conductivity of the stem (W/m*K); A is the stem cross-sectional area (m^2); the temperature gradients are dTu/dX (K/m) and dTd/dX; dX is the spacing between thermocouple junctions. One pair of thermocouples is above the heater and one pair is below the heater as shown on the schematic in Figure 1.

There are two differentially wired thermocouples both measuring the rise in sap temperature. Channel AH measures the difference in temperature A-Ha (mV). Channel BH measures the difference in temperature B-Hb (mV). By subtraction of these two signals:

$$BH-AH = (B - Hb) - (A - Ha) = (B-A) + (Ha - Hb) \qquad (mV)$$

The result yields the two components of axial heat conduction out of the stem section, Qu and Qd. Since the distances, dX, separating the upper TC pair and lower TC pair are fixed by design for each particular gauge to the same value, the components of Qv are combined with a common denominator:

$$Qv = Kst\ A\ (BH - AH)/\ dX * .040\ mV/\ C$$

The factor .040 mV/C converts the thermocouple differential signals to degrees C.

In equation (1) the radial heat loss is computed by:

$$Qr = Ksh * CH$$

For an installation of a fixed diameter, Ksh relates the radial heat flux directly to the thermopile output signal CH as follows. The signal, CH (mV), to the datalogger is directly proportional to the temperature difference between inner and outer layers of the cork substrate surrounding the heater, and it is therefore proportional to the radially conducted heat.

The sheath conductance is calculated when the user establishes a no-flow condition. The calculation for Ksh (W/mV) is determined by solving equation (1) when setting Qf = 0 as follows:

$$Pin = Qr + Qv$$

and since Pin and Qv are calculated in absolute heat or power in W,

$$Qr = Pin - Qv$$

So after computing Pin and Qv at Qf=0,

$$Ksh = (Pin - Qv)/\ CH\ (W/mV)$$

Ksh is measured on excised stems or in pre-dawn conditions for a minimum value. On small diameter plants the user assumes a minimum value of Ksh at a minimum flow rate, the zero set point, and enters the setting as the Ksh constant. The minimum Ksh will occur at the point when CH is at its peak value one to two hours before dawn. When the radial loss is at a maximum it is because the convection heat flux is at its minimum. On large diameter trees, the Ksh setting is more consistent when performed on an excised trunk or wooden post having the same diameter as the trunk.

After solving equation (1) for Qf, the flow rate per unit of time is calculated from the equation for sap flow as described by Baker - Van Bavel (1987).

$$F = (Qf) / Cp * dT \quad (g/s) \qquad (2)$$

Ksh is the thermal conductance constant for a particular gauge installation. Cp is the specific heat of water (J/g*C), and dT is the temperature increase of the sap.

The temperature increase of the sap, dT, is measured in mV by averaging the AH and BH signals , and then converted to degrees C by dividing by the thermocouple temperature conversion constant as follows:

$$dT = \frac{(AH + BH)/2 \quad (mV)}{.040 \ mV/C} \qquad (C.)$$

Recent Dynagage Applications and Advances

Dynagage is the state of the art in sap flow measurement. Since the development of the original portable prototypes, Dynamax has developed the commercially produced versions (See Fig 2) with weather proofing, rugged internal electronics, and installation methods that make the sensor easy to remove and repeat usage on new plants or locations.

* MECHANICAL SPECIFICATIONS

MODEL NO.	SHIELD & GAUGE HEIGHT	STEM DIAMETER RANGE		
		MIN.	TYP.	MAX.*
SGA10-WS	180	9	10	13
SGA13-WS	180	12	13	16
SGB16-WS	200	15	16	19
SGB19-WS	250	18	19	23
SGB25-WS	280	24	28	32
SGB35-WS	460	32	41	45
SGB50-WS	505	45	50	65
SGA100-WS	660	100	110	125

* ALL SPECIFICATIONS IN MILLIMETERS

With the development of complete systems (see systems section) and sensors that are compatible with standardized software, the detailed implementation of the equations in the previous section is transparent to the user. The DGSF, Dynagage sapflow analysis software, computes real time sap flow on CR7, 21X, and the new DNX10 dataloggers based on the CR10. The software is standardized to run on IBM compatible PCs, and is applicable to all

Campbell Scientific dataloggers.

Recent examples of the advanced research made possible by Dynagage are many. Steinberg and Zajicek (1991) were able to determine accurately the effects of chemical growth regulation in comparison to pruning on Hibiscus (*Hibiscus rosa-sinensis L*). The study showed that chemically treated plants used 33% less water than control plants, and that pruned plants used less water initially, but after regrowth, the usage was only 6% less than control, after the end of the 50 day test. Peak flow rates were also affected dramatically on a leaf area basis. For example sap flow was 120 to 160 g $*h^{-1}*m^{-2}$ on the pruned and control plants, nearly three times higher than the 40 to 70 g $*h^{-1}*m^{-2}$ on the chemically treated plants.

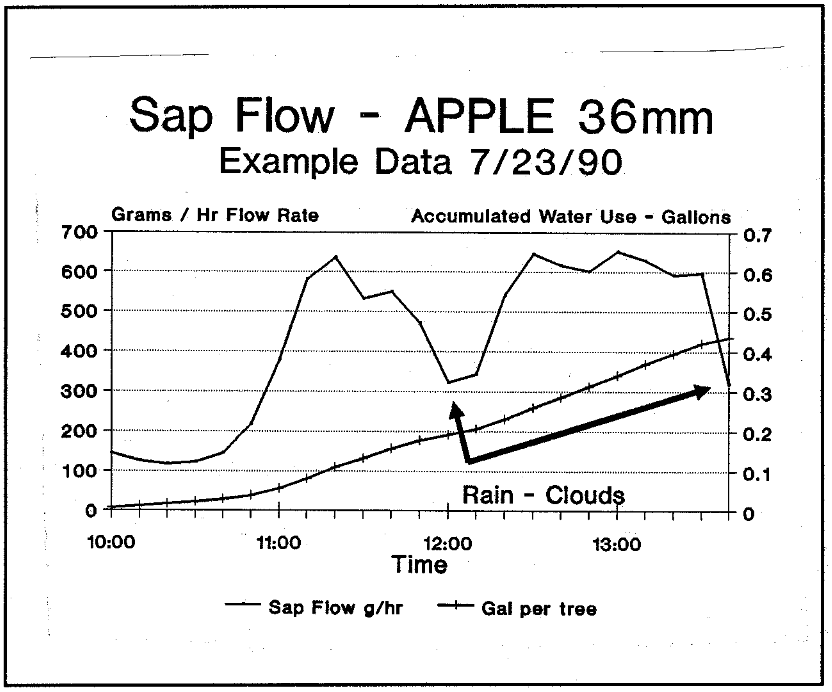
Another example of a similar study by Steinberg and Zajicek(1991) on *Ligustrum Japonicum* showed the short term effects of growth reduction treatments. In this instance, with great contrast to the Hibiscus, growth retardants did not change the flow rate per unit leaf area, but did have a impact on water relations through the decrease in leaf area of the plants. More studies of this nature are planned to relate water use characteristics to the physiology physiology of the plants and the effects of growth regulation.

In the field of range science, Dugas(1991) showed that the removal of honey mesquite (*Prosopi glandulosa*) by diesel fuel defoliation within a mesquite-dominated rangeland decreased the evapotranspiration temporarily by 40%. In the following year however, the rangeland evaporation was only reduced by 7% because other range crops (primarily grasses) grow larger and replace the water use of the mesquites removed. Dugas also showed the quickest way to measure the effect of a pollutant (diesel fuel) on living plants with Dynagage. The transpiration stopped completely within twelve days. Dugas also showed the utility of measuring branch sap flow and relating the number of branch stems per hectare as a useful relationship of sap flow to unit land area. Since the main trunk separates into many smaller branches only a few cm off the ground level, the main trunk is usually not a good place for a stem gauge. In the rangeland study Dugas used the Bowen Ratio method of determining total evaporation, and correlated direct sap flow measurement by Dynagages to these readings.

In a recent Journal of Range Science, Dugas (1992) showed the very close relationships of potential evaporation (PET) to the stem flow of mesquite during well watered conditions, as well as the comparisons of sap flow to gravimetric measurement. The RMSE of 25 g per day was reported for daily transpiration of 1330 g compared to mass lost by weighing, about a 2% error. Typically gauges in this study were placed .3 m above the soil, and on the stems for 25 to 56 days. Dugas showed the effect of drought stress on the sap flow by comparing to the PET under those conditions. In the case of water stress and high demand, the sap flow reflected the PET only in the morning, and by midday the sap flow was reduced considerably relative to PET. Overall 38% less water use was measured on days with similar PE due to the reduced availability of ground water.

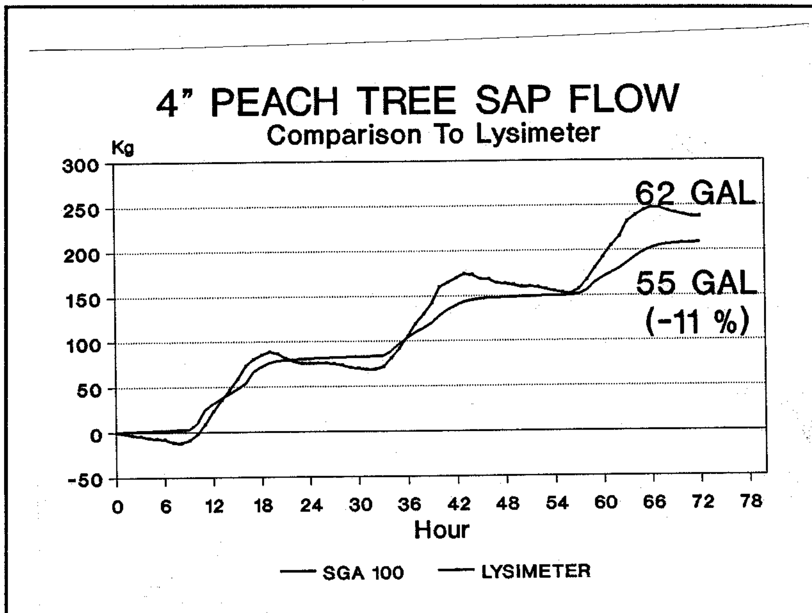
Citrus and Fruit Growing Applications

In tests performed on grape vines, peach and pecan trees in Texas, there are several good examples of relating water use to the environmental conditions and studying the plant response to various water conditions. In addition it is shown that in a low water usage crop such as grape vines, flood-irrigated fields can lose up to 75% of the water to evaporation.



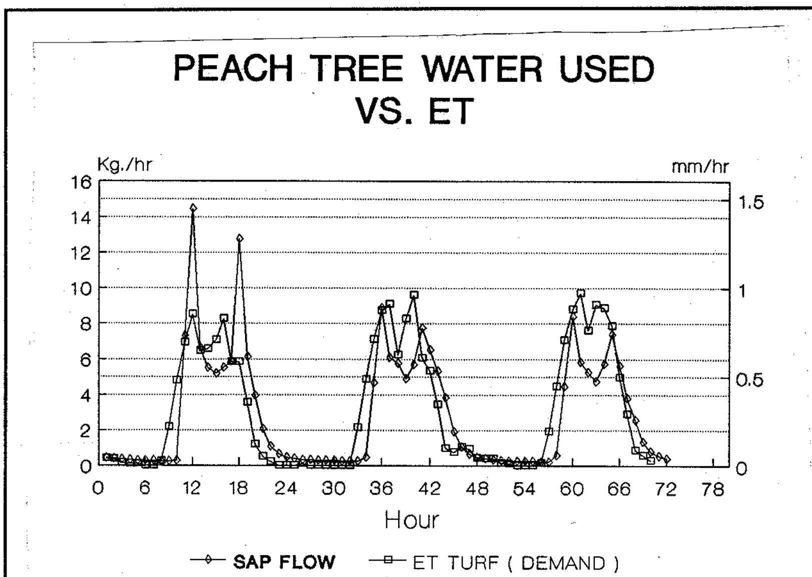
In the example shown in Figure 3, an apple tree water consumption is tracked for the day. The short term effect of clouds and a rain period at 12:00 is easily shown. Note that the sap flow did not come to a total stop for two possible reasons: 1) there is still sunlight coming through the clouds, and 2) the sap flow continues takes time to replenish the water lost by transpiration at the leaves. Typically there is a lag of 30 minutes to an hour between the transpiration and the total sap flow. The clear advantage of this data is a real time evaluation of the water consumed by the crop, equal to 0.44 gallons per plant. This example was taken in a three year old tree of the Granny Smith variety planted in trellised rows (2.5m high and 36mm diameter at the base). The irrigation system can be programmed to replenish the water consumed reflecting the seasonal and daily changes by the environment as well as the growth of the trees.

In a lysimeter study, peach trees 5 m high and with a canopy of 5 m were monitored by the SGA100-ws, a Dynagage with a trunk capacity of 100 to 125 mm diameter. Shown in Figure 4 are three days comparison between a covered lysimeter and the stem flow gauge. The total consumption was 210 kg using the gauge and 235 kg by the lysimeter. Over three days the sap flow was within 4% per day, for a total variance of about 11%. As one can see in the evening data, lysimeters are subject to temperature changes and wind stress changes and drift in measurements.



3 DAY TOTAL

With respect to the application of sap flow measurement to detect water stress, an index of comparison is the ETP computation, or evapotranspiration demand computed from radiation, wind speed, humidity, and air temperature. Dynamax supplies a weather station and preprogrammed software, Penman-van Bavel, to collect and interpret this data. By charting the sap flow rates along of the hourly ETP (in mm/hr), Figure 5 shows the close fit of the sap flow to the demand especially when well watered on the first of three days. Upon close inspection, one notes the demand always leads the sap flow. By the third day, there is a noticeable slump in the sap flow caused by a more limited availability of water. Studies of this type can also



As an example, the Sap Flow decreases when a fixed water supply is depleted with steady demand. Integrating daily values provide the irrigation amount.

be done in place in the orchard by simply keeping one set of trees in good supply of water, measuring total flow (Ftw), replenishing all that is used, and comparing this to the normal field trees (Fts) of similar size and exposure, and establishing the stress index of

Fts/ Ftw = water stress index

expressed as a ratio of the total sap flow of stressed trees to those that are not stressed.

A recent study on Chardonnay grape plants by Lascano (1992) began last year to evaluate the utility of stem gauges and to determine the efficiency of furrow irrigation on a crop about which little is known regarding its water usage. When results were published from the 100 day experiment on grape vines (*Vitis vinefera*) showing the total ET from an irrigated field, and compared to the total sap flow from the grape vines, it was discovered that 77% of the ET was due to soil evaporation. The ET total was confirmed by neutron probe measurements which were correlated to rainfall and irrigation data, and the T was measured by Dynagages. Potted plants were confirmed to have sap flow and gravimetric water loss within 5-10% of each other. This study also showed the utility of normalizing the results of the test plant's sap flow by the leaf area to determine the total water transpired for a given acreage. This method greatly reduces the variability of the data.

Crops Research and Results

Over the last several years Dugas (1990), Ham (1990), Ham (1991), Howell (1991), and Saliendra (1991) have shown the effectiveness of sap flow measurement to study cotton, maize, sorghum and sugarcane. Many additional papers (16) were presented on the utility of sap flow determination of transpiration in a recent Sap Flow Symposium in the American Society of Agronomy, October 1991.

A comparison of the stem flow gauge with a lysimeter on cotton plants (Dugas 1990) showed that the method was accurate for cotton plants (error <+/-10%), however the amount of sap flow varied widely between plants . The coefficient of variation increased as the season progressed, as the sizes of the plants varied more. Later it was shown by Heilman (1990) that by indexing to the leaf area, at least in the case of Ligustrum, the variation in water use between plants is neglegible as long as the exposure is the same. A later publication by Ham (1990) proved that this was also the case for cotton. The clear implication is that determination of the crop water use by a number of plants tested for sap flow should be indexed to the main crop not by the number of plants, but instead the leaf area of the tested plants to the leaf area of the total crop.

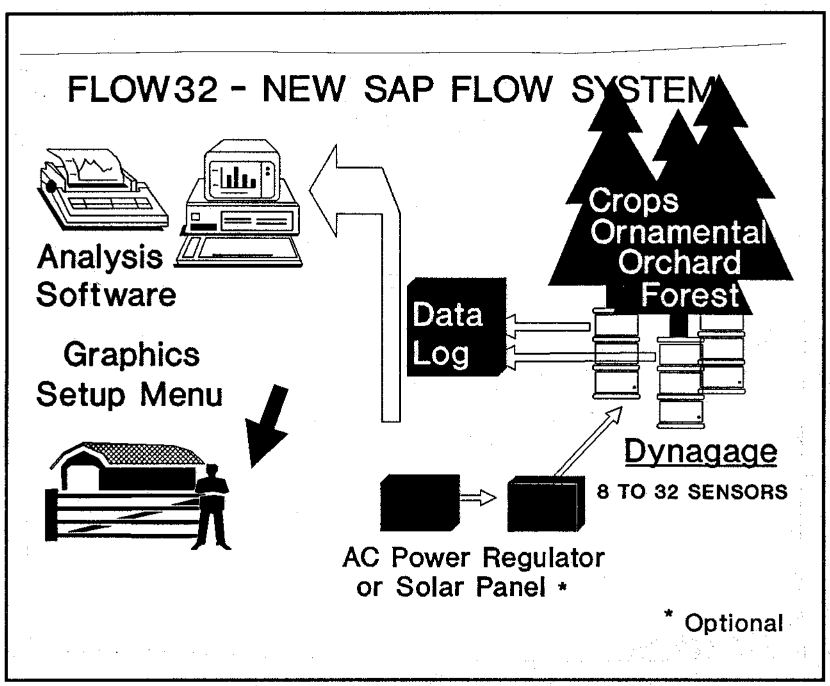
Ham(1991) also separated E from T in a cotton crop using the Bowen Ratio-Stem Flow method. Never performed in this way before, the total ET was determined with the Bowen Ratio method, and T was independently monitored by sap flow gauges. The E was independently checked by microlysimeters. On the average E calculated was within 11% of measured E. Other researchers were successful in performing the same analysis on corn and soybean.

Saliendra (1991) prepared a stem flow driven analysis of three sugarcane (Saccharum) genotypes to look at stomatal conductance and root hydraulic conductance particularly during soil drying. Saliendra found that the genotypes all varied in transpiration at all stages of soil drying. However the conductance:transpiration had a linear relationship for all types. This suggested that liquid water transport efficiency regulates the water vapor loss.

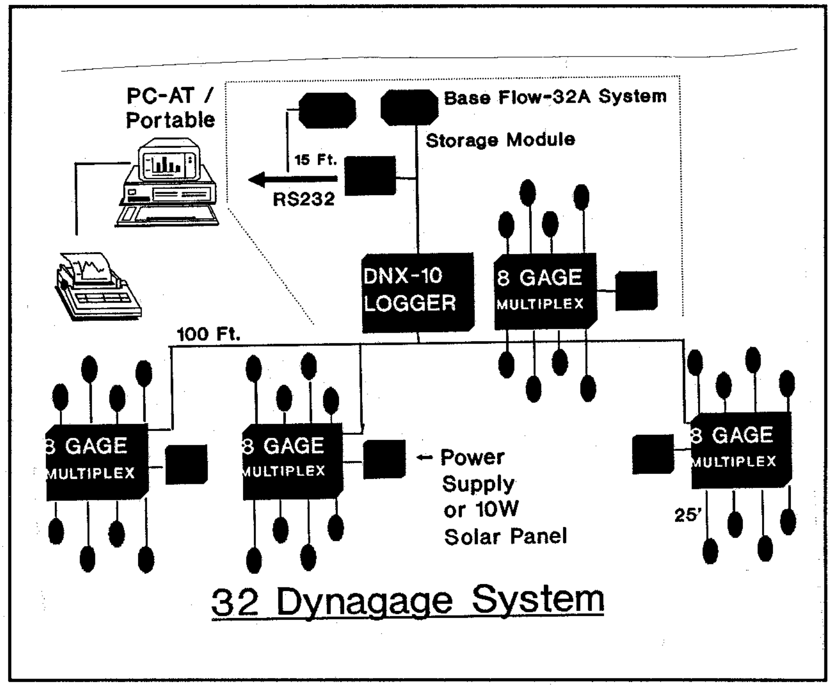
Systems for Monitoring Sap Flow

In the previous studies on sap flow with the SHB sensors, researchers constructed the electronic monitoring system out of available components including dataloggers, cables, custom software, power supplies, and communication or retrieval equipment.

Dynamax Inc, through Irricrop Technologies Ltd in Narrabri, announces at this Irrigation Symposium that the new Flow32 system is now available. Flow32 integrates all of the logging, storage, retrieval, and power functions into a complete package (See Figure 6). IBM PC portables or compatibles are the best choice to load programs and to run formatting or retrieval utilities. The system includes multiplexers, assembled and tested wiring, a solar



panel or 120V power supply, voltage regulators, retrieval cables, data storage modules, and weather proof enclosures. Dynamax therefore designed the system to not only include all of these functions, but to incorporate real-time graphics for environmental control chamber and glasshouse monitoring. The use of menus and other simple software tools were integrated into a fully assembled package which makes system initialization and starting to gather data a much simpler task.



Most importantly, the system will collect data from one to 32 sensors simultaneously. An initial system comprising five sensors and all of the software, the controller, DNX10, and retrieval modules, is called the Flow32-A. As shown in Figure 7, the system can be economically expanded in modules of eight sensors per multiplexer. The Dynamax controller/datalogger is a special version of a CR10 that also retains its general purpose data collection functions.

Summary

In the future more horticulturalists, soil and crop scientists, agronomy, patholology and environmental researchers will be able to make use of the new sap flow technology with much greater ease using Dynagage and the fully integrated Flow32 Systems.

Agricultural engineers in arid lands can efficiently design drip and sprinkler irrigation systems with sap flow information. The closed loop feedback system which determines the application of water from the actual plant use will have the greatest accuracy and therefore yield improvements. Seasonal and weather related variations in water demand are precisely determined for real-time systems, and may provide the fundamental water delivery requirements without resorting to an over design and related extra expense in future systems.

Water management, hydrology, and water quality studies now have the tools to separate water flux into transpiration from the plants vs soil evaporation and leaching. The sap flow information on stream bank vegetation, phreatophytes, and range land invaders such as mesquite, and cedar trees, provides the user with the water flux data that is essentially unavailable from other sources.

The health of a plant may also be monitored by observing the sap flow. Root damages, insect damage and competition with weeds can be quantified and compared to healthy plants, or by observation of the crop over time. Air quality is an increasing area of concern. The effect of pollutants on the process of photosynthesis and transpiration are indirectly measured via sap flow instrumentation, as long as plants can be isolated from the pollution to provide a benchmark against plants in polluted air. The effects of treatments to counter cell destruction by pollution in either the ground water or the air may be established clearly with monitoring by Dynagage.

The use of Dynagage to observe genetic engineered plants for resistance to drought, growth patterns, and fertilizer efficiency are new applications having great benefit to the farming industry.

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